

Ozone quasi-biennial oscillations (QBO), semiannual oscillations (SAO), and correlations with temperature in the mesosphere, lower thermosphere, and stratosphere, based on measurements from SABER on TIMED and MLS on UARS

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[1] The ozone and temperature measurements from Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) on the Thermosphere-Ionosphere-Mesosphere-Energetics and Dynamics (TIMED) satellite form a unique set. They provide global information over the range of local solar times, from the lower stratosphere into the lower thermosphere, going back to 2002, by one instrument. On the basis of zonal means of these data, we present new results from 20 to 100 km in altitude and from 48°S to 48°N in latitude of ozone and temperature semiannual oscillations (SAO) and quasi-biennial oscillations (QBO). While some of the results are new for the stratosphere, such results for the mesosphere and lower thermosphere (MLT) have not been available before. The SAO and QBO components are mostly symmetric with respect to the Equator. The correlations of ozone and temperatures provide the opportunity to study the relative effects of dynamics and chemistry. Our results show that the ozone oscillations are largely and positively correlated to those of the temperature below about 30 km and above 80 km, and mostly anti-correlated with temperature between about 30 and 80 km. We compare with measurements made about 10 years earlier by the MLS instrument on UARS, and with results by others from the solar mesosphere explorer (SME) satellite, the solar backscatter ultraviolet (SBUV), space shuttle experiments (CRISTA), and ground-based measurements.

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1. Introduction

[2] The importance of atmospheric ozone and temperature from both a practical and scientific view is well known. Understanding the global diurnal and mean variations provides important information on the photochemistry, dynamics, and energetics of the atmosphere. However, there has been a relative lack of global measurements in the mesosphere and lower thermosphere (MLT) region. Ozone and temperature data from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument [Russell *et al.*, 1999] on the Thermosphere-Ionosphere-

Mesosphere-Energetics and Dynamics (TIMED) satellite fill this gap. The measurements are unique in the breadth of their information content, being made over the globe from about 15 to 100 km, over 24 h in local solar time (LST), and over multiple years (since the beginning of 2002). This kind of information has not been available previously, especially from one instrument.

[3] We have derived zonal mean ozone mixing ratio and temperature variations from 20 km to 100 km, 48°S to 48°N latitude, and 0 to 24 h local solar time, using data from SABER for years 2002 through 2005. In this paper, we focus on new zonal mean results of ozone and temperature semiannual oscillations (SAO) and quasi-biennial oscillations (QBO), and compare with some corresponding results based on data from the Microwave Limb Sounder [MLS, Barath *et al.*, 1993] on the Upper Atmosphere Research Satellite [UARS; Reber, 1993], measured from 1992 into 1994. Comparisons are also made with other results in the literature, although comprehensive global results have not been available previously, especially in the mesosphere and lower thermosphere. We also analyze the correlations be-

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tween the temperature and ozone SAO and QBO, which can indicate the relative roles of chemistry and dynamics. Results for the ozone diurnal variations covering 24 h in local time, over the same temporal and spatial range as for the SAO and QBO, are described in *Huang et al.* [2008].

[4] In section 2 we discuss the data sampling and analysis, and the special sampling characteristics of SABER (and MLS) in local time. Although SABER and UARS measurements provide information over the full range of local times, the measurements are still synoptic, and the analysis is not straightforward. Nevertheless, SABER and MLS provide the potential to realistically estimate both global diurnal variations and zonal mean variations (SAO, QBO) over an annual cycle (or more) that are not provided by data from other sources, such as other satellites, ground-based radiometers, and in situ measurements. In section 3 we consider the data quality for SABER and some other measurements. In section 4 we present results of mean variations of the ozone SAO and QBO, and their correlations with corresponding variations in temperature.

2. Data Sampling and Analysis

2.1. Data Characteristics and Analysis Algorithm

[5] Our results are derived from version 1.06 of SABER level 2A data, which are provided by the SABER project for years 2002 through 2005. The SABER instrument views the earth's limb, and ozone emissions in the $9.6\ \mu\text{m}$ band are used to retrieve the mixing ratios. The data are interpolated to 4° latitude intervals and 2.5 km altitude intervals from 20 to 100 km, and averaged each day over longitude for analysis.

[6] Although SABER on TIMED and MLS on UARS sample over the range of local times, they need 60 and 36 days respectively, to do so. Over a given day and for a given latitude circle, measurements are made as the satellite travels northward (ascending mode) and again as the satellite travels south (descending mode). Data at different longitudes are sampled over one day as the earth rotates relative to the orbit. The orbital characteristics of the satellite are such that over a given day, for a given latitude circle, and a given orbital mode (ascending or descending), the local time at which the data are measured are essentially the same, independent of longitude and time of day. If we work with data averaged over longitude, for each latitude and altitude, we get 2 data points for each day, one for the ascending mode and one for the descending mode, each corresponding to one local solar time, and each can be biased by the local time variations. True zonal means are averages made at a specific time (not over a day) over longitude around a latitude circle, with the local solar time varying by 24 h over 360° in longitude. The local times of the SABER measurements decrease by about 12 min from day to day, and it takes 60 days to sample over 24 h in local time. Although this provides essential information in local time, over 60 days, variations can be due to both local time and other variables on seasonal and other time scales. Diurnal and mean variations are embedded together in the data, and need to be unraveled from each other to obtain more accurate estimates of each.

[7] Our algorithm is designed for this type of sampling in local time, and provides estimates of both diurnal and mean variations together in a consistent manner. It attempts to

remove the bias in the mean due to the local time. At a given latitude and altitude for data over a period of a year or more, the algorithm performs a least squares estimate of a two-dimensional Fourier series where the independent variables are local solar time and day of year, and variations as a function of local time and mean variations are generated. We currently do not generate results poleward of 48° because data exist at higher latitudes only on alternate yaw intervals (60 days). Because it takes SABER 60 days (36 days for MLS) to sample 24 h in local time, the information about seasonal variations of the diurnal variations themselves may be limited, and we limit the number of coefficients estimated as described in the Appendix.

[8] Once the coefficients are estimated, both the mean components and the variations with local solar time can be calculated directly for any day of year. The algorithm (see Appendix) has been applied previously to SABER temperature measurements of diurnal variations (thermal tides) and mean variations to study intra-seasonal (ISO), semiannual (SAO), and quasi-biennial (QBO) variations [*Huang et al.*, 2006a, 2006b, 2006c]. It has also been successfully applied to wind measurements from the TIMED Doppler Interferometer (TIDI), as described by *Huang et al.* [2006a], and to MLS ozone measurements [*Huang et al.*, 1997].

[9] Figure 1 shows an example of the sampling properties of SABER data and how well our algorithm fits the data. SABER ozone (parts per million by volume, ppmv) data, averaged over longitude, at the Equator and 90 km altitude, are plotted versus day for year 2005. For a given day, the red solid and green dashed lines represent the data averaged over longitude from the ascending (satellite going northward) and descending modes, respectively, each corresponding to one local time. As can be seen, the two data points for each day can differ by up to several ppmv, reflecting different local times. The local times decrease by about 12 min from day to day. The blue diamonds and black squares depict our estimates, evaluated at the same day and same local time as the data. As can be seen, the estimates approximate the measurements reasonably, although there are some intervals over several days where our estimates do not follow the data as well, so some smoothing exists. At 90 km, the amplitudes of diurnal variations are larger than those at lower altitudes, with the nighttime values being up to an order of magnitude larger than daytime values, thereby testing the algorithm more than at lower altitudes.

[10] Figure 1 also shows the advantages of our algorithm. For example, our estimates follow the individual data points (solid and dashed lines) fairly well. This is better than grouping or making composites of the data over 60-day bins (the period needed to sample the data over the range of local times), which can smooth the results.

2.2. Ozone Morphology

[11] Before discussing our results for the QBO and SAO, we first give an example of the general nature of the derived ozone mixing ratios. Figure 2 shows examples of zonal mean ozone mixing ratios (parts per million by volume, ppmv) on altitude (20 to 100 km) versus latitude (48°S to 48°N) coordinates, for day 85, based on SABER data from different years (2002–2005) merged into one 365-day period. What makes the left plot of Figure 2a different from previous plots of this type, aside from the large altitude

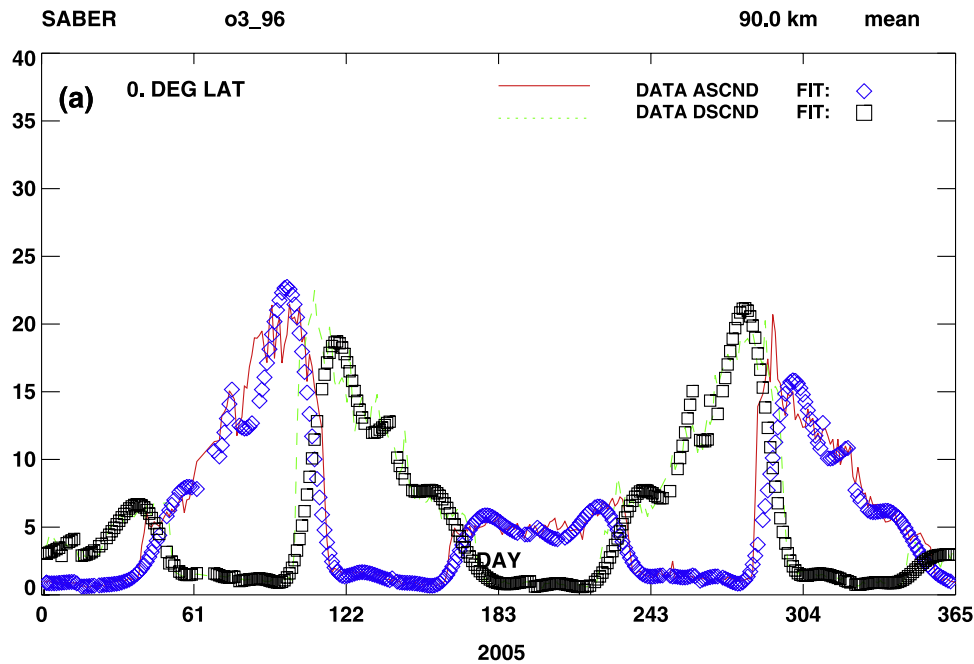


Figure 1. Zonally averaged SABER ozone data (ppmv) and estimated results plotted versus day of year for 2005, at the Equator and 90 km. Solid line and diamonds represent ascending mode data and fit, respectively. Dashed line and squares represent descending mode data and fit, respectively.

range, is that it shows our derived zonal mean values that are averages over both local time and longitude in a consistent manner. Previous results based on other satellite data usually correspond to one local time, as in the right plot of Figure 2(b), which are evaluated from our estimates for 16 hrs local time, and correspond to the local times of measurements from the solar mesosphere explorer (SME). The differences between the left and right plots are not significant in the middle and lower stratosphere, where diurnal variations are relatively small, but are evident in the upper stratosphere, mesosphere, and higher. It can be seen that

from the upper stratosphere on up, the daytime values (right plot, at 16 h local time) are generally smaller than the values in the left plot, where the variations over local time are averaged out. For example, between 90 and 100 km, the peak values in the left plot approaches 11 ppmv while the corresponding peak in the right plot is about 3 ppmv.

3. Data Quality and Previous Measurements

3.1. Previous Measurements

[12] In past decades, satellite-borne instruments have provided invaluable global measurements of ozone. The

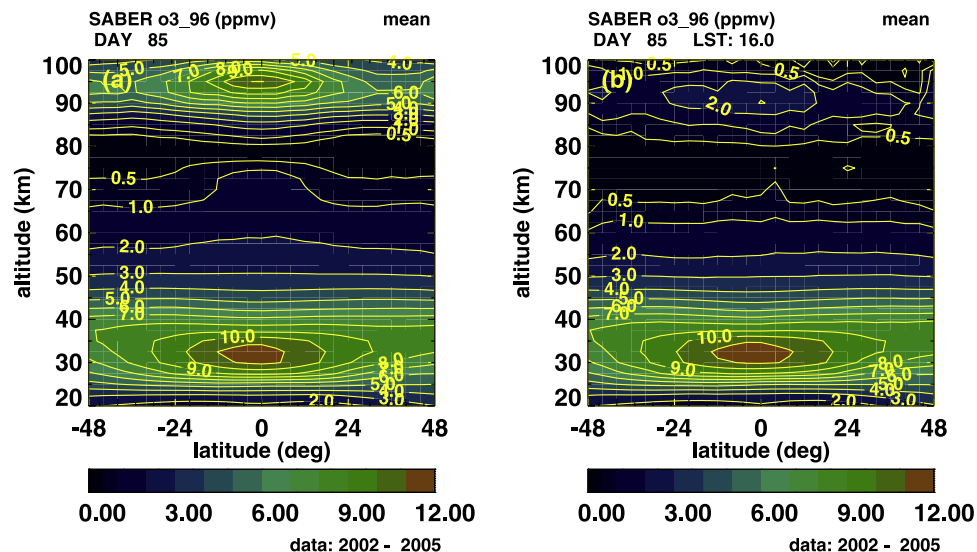


Figure 2. Derived zonal mean ozone mixing ratios (ppmv), based on SABER data combined from years 2002–2005, on altitude (20 to 100 km) versus latitude (48°S to 48°N) coordinates, for day 85. Left: mean values that are averages over both local time and longitude; Right: corresponds to left plot but at 16 h LST.

preponderance of the measurements has been made in the stratosphere and below, where diurnal variations are relatively small, and there have been a lack of measurements in the mesosphere and above, where diurnal variations can be dominant, due to photochemistry and to transport.

[13] Unlike UARS and TIMED, the orbital characteristics of other satellites, and/or the length of their missions (e.g., space shuttle missions), are such that the data are taken over a limited range of local times. Most satellite orbits are sun-synchronous, so that the local times at which measurements are made do not change from day to day, and remain the same for the duration of the mission. In these cases, when diurnal variations are not negligible, it is impractical to quantitatively analyze the measurements for their behavior as a function of local time and to estimate unbiased zonal mean values. Examples of other satellites that sound the atmosphere to obtain ozone profiles include SME [Barth *et al.*, 1983], the Nimbus satellites, the Earth Observing System (EOS) satellites, the NOAA polar orbiters, and selected space shuttle missions [Kaufmann *et al.*, 2003]. Measurements from these satellites do not provide the sampling needed to quantitatively analyze variations over the 24 h of local times. For example, the ozone measurements made by SME are all made essentially at one local time (~ 16 h), irrespective of longitude and day. The Halogen Occultation Experiment (HALOE) on UARS measures ozone only during sunset and sunrise. Ricaud *et al.* [1996] have presented diurnal variations of ozone based on MLS on UARS for some sample cases. They note, as we did earlier, that if there are trends in the 36 days it takes to sample the data over the range of local times, then changes in ozone may well be induced more by monthly variations than by diurnal effects in the sampled data. They therefore restricted their analysis to cases in a small altitude interval near 55 km, where the diurnal variations are larger than 10% of the diurnal average. Wu and Jiang [2005] have analyzed ozone and temperature data from a more recent version of MLS data, but their results do not contain the details needed for comparison.

[14] Over the decades, ground based measurements [e.g., Schneider *et al.*, 2005; Zommerfelds *et al.*, 1989; Connor *et al.*, 1994] have provided ozone and temperature measurements as a function of local time with good time resolution, from about 25 to 75 km, but do not provide good global coverage.

3.2. Data Quality

[15] From the middle mesosphere to higher altitudes, departures from local thermodynamic equilibrium (non-LTE) can be significant, complicating the retrieval of ozone mixing ratios, and the uncertainties can be larger than those at lower altitudes. In the final analysis, validation depends on comparisons with 'ground truth'. However, there is a clear lack of correlative measurements in the mesosphere and lower thermosphere (MLT). This situation is exacerbated by diurnal variations of ozone, which can be several times larger at night compared to daylight. If correlative measurements are not available at both the same time, especially local solar time, and location, discrepancies can be relatively large and the causes difficult to pin down. As discussed below, it is currently difficult to reach definite

conclusions in comparing with past measurements, especially in the upper mesosphere and lower thermosphere.

[16] Of the data sources mentioned above, the more relevant ones are the Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA) [Kaufmann *et al.*, 2003] and SME [Thomas, 1990, Barth *et al.*, 1983]. CRISTA was flown on two space shuttle missions in November 1994 (CRISTA-1) and August 1997 (CRISTA-2), each with measurements lasting a little more than one week, from 50 to 95 km. The short duration resulted in limited sampling over local time, and results were given at selected daytimes and nighttimes. The SME provided ozone measurements from about 50 to near 90 km, but only at ~ 16 h local time. Additional measurements are provided by ground-based radiometers [e.g., Zommerfelds *et al.*, 1989; Connor *et al.*, 1994; Schneider *et al.*, 2005]. The sampling and resolution in local time is better, but the spatial coverage is limited, and the altitude resolution is not as good that of CRISTA or SME.

[17] Figure 3 shows the fitted SABER results along with those of Kaufmann *et al.* [2003], transcribed by us from their Figure 13a, which show CRISTA-1 and CRISTA-2 results, plus MLS data. The asterisks depict the fitted results (44°S latitude, 0 h LST). The left plot is for day 220 (8 August) and the right plot is for day 310 (6 November). The left and right plots contain the same data for CRISTA-1, CRISTA-2, and MLS. Squares denote CRISTA-1 (mean of 120 profiles, 4–12 November 1994, $40\text{--}55^\circ\text{S}$ latitude, 23–3 h LST) results, the triangles denote CRISTA-2 (mean of 17 profiles, 8–16 August 1997, $40\text{--}55^\circ\text{S}$ latitude, 23–3 h LST) results, and diamonds show MLS (August 1992, $40\text{--}55^\circ\text{S}$ latitude, 23–3 h LST) results, on altitude versus ozone coordinates (semi-log).

[18] As noted earlier, the uncertainties of ozone measurements in the MLT can be relatively large. Kaufmann *et al.* [2003] report that the CRISTA-1 and CRISTA-2 systematic errors in the mesosphere can be as large as 40%. In their comparison with HRDI and MLS, below the ozone minimum (~ 75 km), the CRISTA, HRDI, and MLS profiles differ by less than 30%, usually less than their individual uncertainties. However, near 75 km and above, the systematic errors and standard deviations can be much larger. As they state, "the two CRISTA profiles agree well below 75 km, but above this altitude the CRISTA-2 profile is higher by up to a factor of 5." Comparisons with MLS are also not good at these altitudes, and cannot be reconciled by uncertainties in CRISTA and MLS results, which together can exceed 100%.

[19] Zommerfelds *et al.* [1989] have compared their ground-based ozone measurements with SME data from about 50 to 75 km. They compared data for December and April, although not in the same years. For April, they state that the with the exception of their value near 68 km, error bars for the two profiles generally overlap. For December, Zommerfelds *et al.* [1989] state "the retrievals for December show more substantial disagreement not only in absolute values for mixing ratios but for the general shape of the vertical profiles". Marsh *et al.* [2002] provide mesospheric daytime ozone measurements derived from HRDI measurements on UARS. The upper limits of the standard deviations and systematic errors appear to approach 50%, and they note that SME systematic uncertainties are comparable,

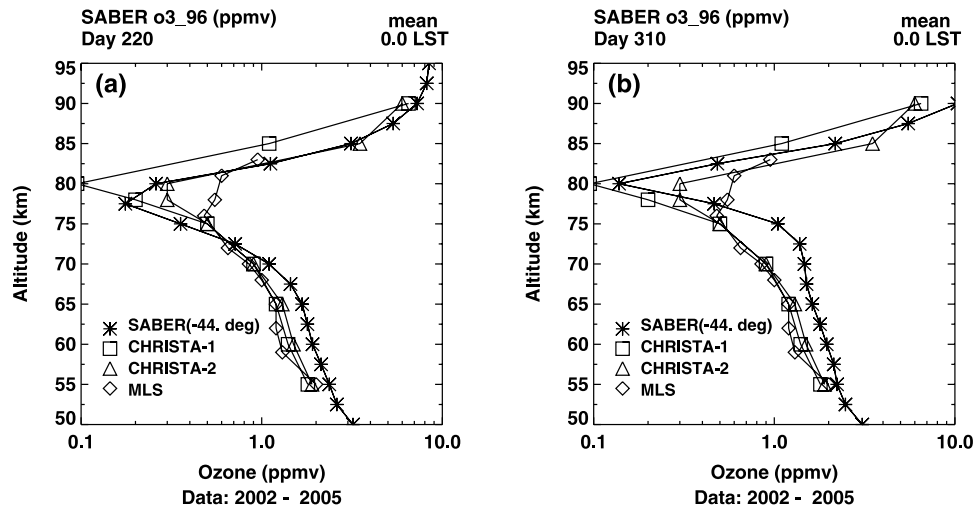


Figure 3. Our derived results (asterisks, 44°S latitude, 0 h LST), CRISTA-1 (squares: mean of 120 profiles, 4–12 November 1994, 40–55°S latitude, 23–3 h LST), CRISTA-2 (triangles: mean of 17 profiles, 8–16 August 1997, 40–55°S latitude, 23–3 h LST), and MLS (diamonds, August, 1992, 40–55°S latitude, 23–3 h LST) results on altitude versus ozone coordinates. For our results, the left plot is for day 220 (8 August) and the right plot is for day 310 (6 November). Left and right plots contain same data for CRISTA-1, CRISTA-2, and MLS.

while SME random errors are $\sim 10\%$ below 80 km and 20% near 90 km.

[20] The magnitudes of uncertainties for the current data version of SABER ozone are comparable to the above estimates for CRISTA and SME. The difficulties in reaching conclusions are evident, as the comparisons are tenuous. In addition, our focus here is on the ozone QBO and SAO, and in the MLT, there are no previous ozone results with which to compare, and an estimate of uncertainties would not by themselves validate the results. However, the ozone QBO and SAO variations are relative to a mean state and they should be more robust, as this mitigates the uncertainties of systematic errors. In any case, the QBO and SAO amplitudes are generally but a few percent of the mean state, and independent checks are needed to verify the validity of these variations. As discussed below, our approach here is to examine sensitivity to relative variations in the data, and to analyze the expected correlations between ozone and temperature QBO and SAO, and they will lend confidence to the validity of the results.

[21] We begin with the left plot of Figure 4a, which shows SABER ozone data zonally averaged separately for ascending and descending modes, year day 2005060, versus altitude. The asterisks correspond to ascending mode data at ~ 2 h local time, and diamonds denote descending mode data at ~ 17 h. The lines denote our derived estimates evaluated at those local times. As can be seen, with the exception of a narrow altitude interval near 80 km, the mean daytime ozone mixing ratios are generally smaller than the corresponding values at night. Importantly, this is consistent with the ROSE model [Smith, 2004, Figure 4], where the mean daytime values are larger than the mean nighttime values only near 80 km. This helps verify the precision of relative variations in the measurements. The right plot of Figure 4(b) corresponds to the left plot but shows our estimates (line) at 16 h local time and 44°N latitude, and the '+'s denote SME results (for March, 45°N latitude) that

we transcribed from Figure 1c of Thomas [1990]. The graphs of Thomas [1990] are in units of pressure, so there may be a small vertical shift relative to our results. Ironically, this better-than-expected comparison is probably fortuitous because the systematic uncertainties are significantly larger. What is more significant is the 'bulge' between 75 and 80 km in both of the results, and the small amplitude of the bulge demonstrates the sensitivity of the SABER data to relative variations. The bulge(s) is a systematic feature of the SME data, and has been noted by Bevilacqua *et al.* [1990], Marsh and Smith [2003], and Zommerfelds *et al.* [1989]. Although it is not our intent here to interpret the physics of the bulge, but to study it in terms of the validity of our results, we believe that the bulge may well be due to the local time at which data were taken, and is a reflection of ozone diurnal variations. Our results also show that, averaged over local time, the bulges are no longer apparent, indicating that the SME bulges are likely due to the local time at which the data were sampled (~ 16 h local time). Recall that our results show that only in this altitude interval around 80 km are the ozone daytime mixing ratios larger than the nighttime values.

[22] The likelihood of (a) the bulges being in both the SME and in our results near 80 km, (b) the ozone day time concentration being larger than the night time concentration only near 80 km, and (c) the agreement of (b) with the ROSE model all being coincidental is obviously low. In addition, our results show that the diurnal variations themselves follow a semi-annual variation, which is consistent with the reported semi-annual variation of the bulges in the SME data.

4. Results: Mean Values and Correlations of Ozone and Temperature

[23] In addition to the discussion concerning Figure 4, our approach to analyzing the validity of our results is to analyze correlations with the corresponding temperature

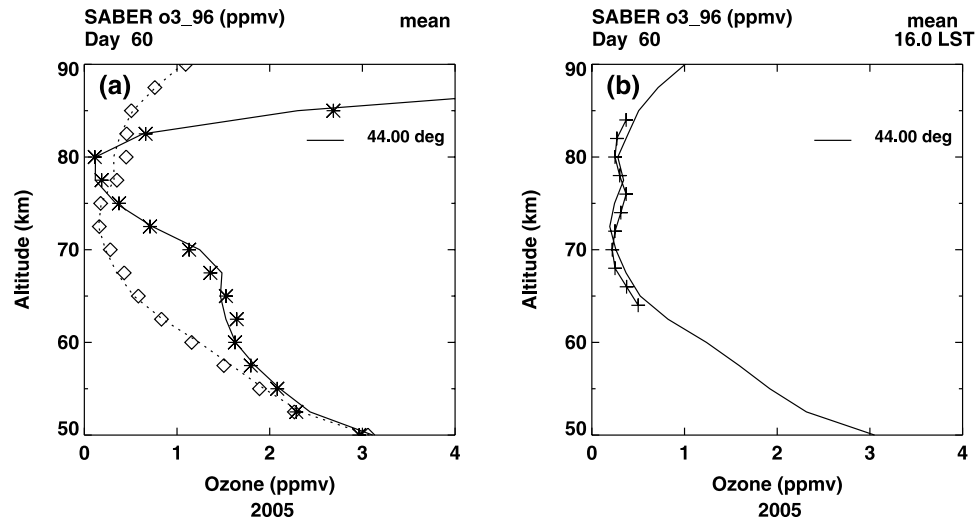


Figure 4. Altitude versus zonal mean ozone mixing ratios (ppmv). Left (a) zonal mean of saber data for year day 2005060; asterisks: ascending mode data (~ 2 h LST), diamonds: descending mode data (~ 17 h LST); lines: our derived estimates. Right (b): ‘+’: SME data at 45°N latitude for March, ~ 16 h local time; line: our estimates at 16 hours local time, based on SABER data for year day 2005060

QBO and SAO, also derived from SABER data [Huang *et al.*, 2006c]. As shown below, the expected correlation (anti-correlations) between ozone and temperature QBO and SAO will lend confidence to the validity of the results. Also, in contrast to the MLT, there are previous empirical ozone results in the stratosphere, and comparisons with our results are discussed below.

[24] In the upper stratosphere, anti-correlations between ozone and temperature measurements have been noted by Barnett *et al.* [1975], and Finger *et al.* [1995], among many others. On the basis of chemistry, the dependence of reaction rates on temperature leads to a negative correlation between ozone and temperature perturbations. However, Rood and Douglass [1985] and Douglass *et al.* [1985] show that dynamics can also cause significant anti-correlations between temperature and ozone, so the situation may not always be simple to interpret. Brasseur and Solomon [2005] provide estimates of spatial areas in the atmosphere comparing the relative importance of chemistry versus dynamics for ozone.

[25] We present ozone and temperature mean variations in the form of quasi-biennial (QBO) and semiannual oscillations (SAO) from 20 km to 100 km, and from 48°S to 48°N latitude. We compare the ozone QBO and SAO with past results in the stratosphere and with corresponding temperature results, also based on SABER measurements, which can give some indication of the role of dynamics compared to chemistry. Finger *et al.* [1995] analyzed ozone data from the Solar Backscatter Ultraviolet Radiometer (SBUV) and the temperature analysis from the National Centers for Environmental Prediction, Climate Prediction Center (NCEP/CPC) taken over more than a decade. Generally, they found an overall positive correlation between ozone and temperature in the lower stratosphere and a mostly negative correlation in the upper stratosphere. Our results show ozone and temperature (SAO, QBO) mostly out of phase from about

80 km down to about 35 km, and mostly in phase from about 20 to 35 km and from about 80 to 100 km.

4.1. Quasi-Biennial Oscillation (QBO)

[26] Quasi-biennial oscillations (QBO) are characterized by periods, phases, and amplitudes that are not fixed. On average, the periods are somewhat larger than two years. Using the same algorithm as in this work, Huang *et al.* [2006c] estimated QBOs based on SABER temperature measurements, and demonstrated very good comparisons with previous results in the literature. In the analysis presented here, we estimate the QBO ozone component by assuming a period of 26 months. As done by Huang *et al.* [2006c], we have also used other periods such as 28 and 30 months. Although the salient features of the derived QBOs are mostly robust for the various assumed periods, it appears that the QBO amplitudes are more prominent for a period of 26 months (in particular the maximum between 90 and 100 km in Figure 7a, top left).

[27] Figure 5 shows derived QBO results based on SABER ozone mixing ratios (left plots, ppmv) and temperatures (right plots, K) at the Equator on altitude (20–100 km) versus day coordinates. Solid contour lines denote zero and positive values, while dashed lines denote negative values. The upper row is based on data from year days 2002001 to 2004060, assuming a period of 26 months, with the abscissa plotted over 2 cycles. The lower row corresponds to the top row but is based on data beginning two years later, from year days 2004001 to 2006060. Comparison between the upper and lower rows is consistent with the QBO having somewhat variable periods, phases, and amplitudes. The general phase relationships between the ozone and temperatures remain, supporting the validity of the QBO in our results. Between about 30 and 80 km, ozone and temperature are mostly out of phase with each other in day of year. Below about 30 km and above 80 km, the

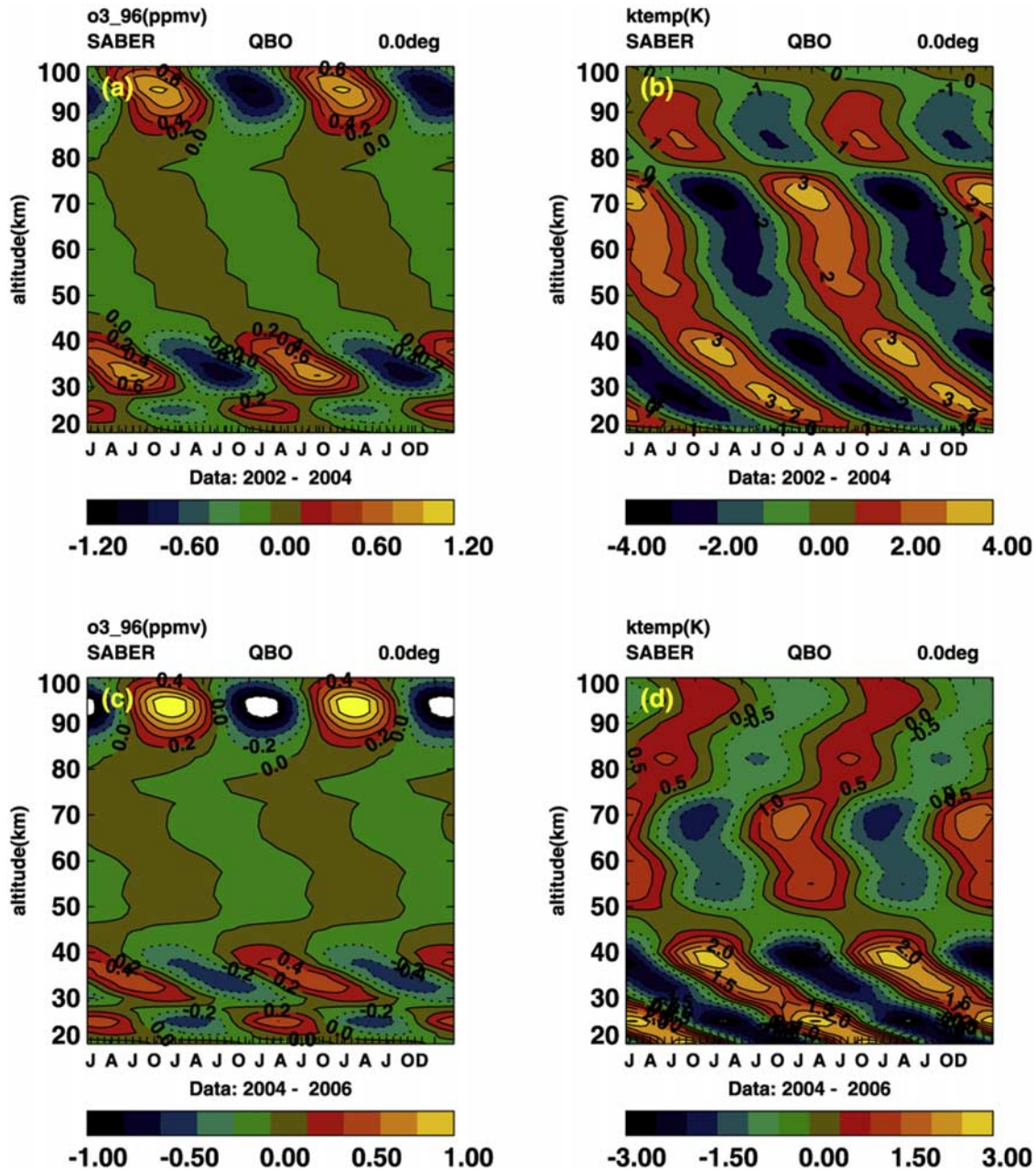


Figure 5. QBO results based on SABER ozone mixing ratios (ppmv) and temperatures (°K) at the Equator on altitude (20–100 km)-day coords. Contour intervals are 0.2 ppmv for ozone, and 1 K for temperature. Solid contours denote zero and positive values; dashed lines, negative values. Top left (a): ozone (ppmv). Top right (b): temperature (°K). Based on data from year days 2002001 to 2004060. Period of 26 months assumed in estimate, abscissa ranges over 2 cycles. Lower row: as in top row but based on data from year days 2004001 to 2006060.

ozone and temperature QBOs are more in phase. Portions of Figure 5 are plotted in Figure 6 to better show the details.

[28] The upper row of Figure 6 shows that portion of the upper row of Figure 5 between 20 and 50 km altitude to present the details more clearly. Solid contour lines denote zero and positive values, while dashed lines denote negative values. Near 28 km, the QBO ozone mixing ratios (left, a) undergo relatively sharp changes with altitude. Below about 28 km, the ozone and temperature (right, b) are just about in phase with each other as a function of day of year. Above

this altitude, the ozone and temperature are mostly out of phase. The rapid change of phase in ozone near 28 km is consistent with past observations of the QBO given by Zawodny and McCormick [1991], Hasebe [1994], and Tian *et al.* [2006] using SAGE II data, and with results from Hollandsworth *et al.* [1995] using SBUV data, which show a phase shift near 31 km. Logan *et al.* [2003], analyzed ozonesonde measurements made at Nairobi, Kenya (1°S, 90°W) and San Cristobal, Galapagos (1°S, 90°W), among other tropical stations. Strong correlations between temper-

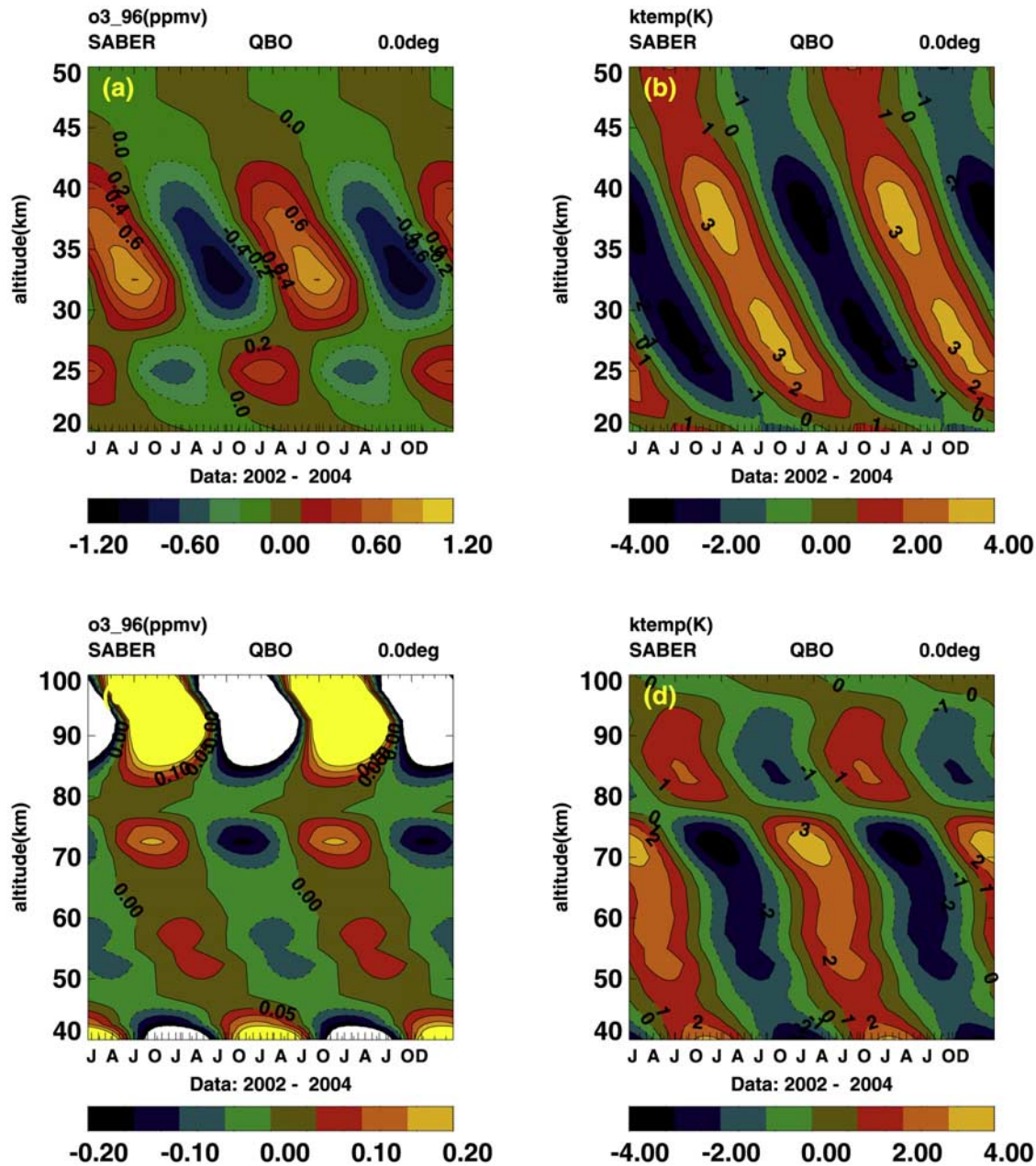


Figure 6. Subset altitudes of Figure 5 to show the results more clearly. Upper row, portions of upper row of Figure 5 between 20 and 50 km altitude. QBO results based on SABER ozone (ppmv, left (a)) and temperatures (K, right (b)) at the Equator on altitude (20–50 km)-day coordinates. The plots are over 2 cycles. Contour intervals are 0.2 (top row left) and .05 ppmv for ozone, and 1 K for temperature. Solid contours denote zero and positive values; dashed lines, negative values. Lower row: Corresponds to that portion of upper row of Figure 5 between 40 and 100 km to show more details. The ozone and temperatures remain mostly out of phase with increasing altitude up to about 80 km. Between 75 and 80 km, the temperature changes phases rapidly with altitude, so that above about 80 km, the ozone and temperature QBO are again mostly in phase with respect to day of year. The plots are over 2 cycles.

ature and ozone from 20 hPa to 95 hPa (~ 27 and 16.5 km) were found. Around 13 hPa (~ 29.5 km), where ozone is influenced more by photochemistry, there is ‘less coherency’, and near 8 hPa (~ 33 km) there is evidence of anti-correlation. The sonde data also show the change of phase in ozone near 29 km (~ 14 hPa), consistent with SAGE II data. In the lower stratosphere, they found that the amplitude of the

ozone QBO (based on sonde data) is ‘much larger than indicated by previous analyses of SAGE II data [Zawodny and McCormick, 1991; Hasebe, 1994]’, and they suggest that the difference is likely due to the lower spatial resolution of the SAGE II data.

[29] The stratospheric QBO has been simulated by various 1-, 2-, and 3-dimensional models, including those of

Ling and London [1986], Gray and Pyle [1989], Hasebe, [1994], Butchart *et al.* [2003], and Tian *et al.* [2006], with attendant differences in assumptions and complexities among the models.

[30] The lower row of Figure 6 shows that portion of the upper row of Figure 5 between 40 and 100 km. We have allowed the scales to saturate (near 40 km and above ~ 85 km) in order to show the smaller values between 45 and 85 km more clearly. It can be seen that the ozone and temperatures remain mostly out of phase with increasing altitude up to about 75 km. Between 75 and 80 km, the temperature phases change rapidly with altitude, so that above about 80 km, the ozone and temperature QBOs are again more in phase with respect to day of year. Burrage *et al.* [1996], using data from HRDI on UARS, presented evidence of the equatorial zonal mean zonal wind QBO near 85 km (MQBO), in addition to the corresponding SAO (MSAO) near 80 km.

[31] The probability that the data display the expected phase relationships between ozone and temperature from the stratosphere into the mesosphere and higher is fortuitous is extremely small and attests to the validity of the results.

[32] The top row of Figure 7 shows the derived QBO amplitudes (left) and phases (right, month of maximum value) based on SABER ozone mixing ratios (ppmv) from year days 2002001–2004060, on altitude (20 to 100 km) versus latitude (48°S to 48°N). The lower row corresponds to the top row, but for temperatures (K), also based on SABER measurements. At low latitudes, there are local maximums in ozone near 30, 55, 70, and 95 km. Ozone and temperature are more in phase above about 80 km, and more out of phase with each other between about 35 and 80 km.

4.2. Semiannual Oscillation (SAO)

[33] Figure 8 shows our derived semiannual amplitudes and phases (month of maximum value) based on SABER ozone mixing ratios (ppmv, upper row) and temperatures (K, lower row), based on data from years 2002–2005, on altitude (20 to 100 km) versus latitude (48°S to 48°N). As noted in Huang *et al.* [2006c], our SAO temperatures and phases agree well with those found by Remsberg *et al.* [2002], based on HALOE measurements on UARS. Although Remsberg *et al.* [2002] do not provide results above 80 km, the amplitude peak in temperature near 90 km is supported by the analysis of Garcia *et al.* [1997], based on temperature data from SME.

[34] For ozone mean variations over an annual cycle, we find that at low latitudes in the mesosphere and above, the more significant component is the semiannual oscillation (SAO), which can approach 2 to 4 ppmv between 85 to 100 km, while near 30 km, the annual oscillation (AO, not shown) is somewhat larger in amplitude compared to the semiannual component, which is about 0.5 ppmv in magnitude. As can be seen from Figure 8, at low latitudes, there are local maximums near 30, 70, and 95 km for the ozone amplitudes. Not as discernable is another maximum of about 0.25 ppmv in amplitude near 55 km. It can also be seen that the semiannual phases of ozone and temperature are mostly symmetric about the Equator, and are also mostly out of phase with each other between about 35 and 80 km. Within about 40° of the Equator and above about 80 km, the semiannual components of the ozone and temperature are consistently in

phase with each other due to a rapid change in phase of the SAO temperature with altitude near 80 km. The ozone and temperature are also more in phase below about 35 km.

[35] The top row of Figure 9 depicts a subset of the top row of Figure 8 to better show details from 20 to 50 km, and to compare with corresponding results based on MLS data (bottom row, Figure 9). It shows derived semiannual amplitudes (left) and phases (right) based on SABER ozone mixing ratios (years 2002–2005), on altitude (20 to 50 km) versus latitude (32°S to 32°N) coordinates. The lower row of Figure 9 corresponds to the top row, but is based on MLS ozone mixing ratios (years 1992–1994), on altitude (100 to 1 hPa, about 16 to 48 km) versus latitude (32°S to 32°N). It can be seen that the SABER and MLS SAO compare well. As an aside, the two small maximums near 10 hPa (about 30 km) on either side of the Equator seen in the MLS results agree with the results of Ray *et al.* [1994], also based on MLS data. There is also good agreement with corresponding results of Perliski and London [1989], based on nine years (October 1978–September 1987) of Nimbus-7 SBUV measurements.

[36] To get a different perspective, Figure 10 shows derived semiannual ozone mixing ratios (ppmv) and temperatures (K) at the Equator (upper row) and 40°N latitude (lower row) on altitude (20 to 100 km) versus day coordinates based on SABER data (years 2002–2005). The left plots of each row (a, c) show ozone mixing-ratios (ppmv) and the right plots (b, d) show temperature results. Solid contour lines denote zero and positive values, while dashed lines denote negative values. As noted in Huang *et al.* [2006c], the temperature SAO at the Equator (Figure 10b) agrees well with corresponding results from Garcia *et al.* [1997], based on temperature data from the SME and from rocketsondes at Kwajalein (8.7°N , 167.7°W) and Ascension (7.6°S , 14.4°W) islands. Above 85 km, we allow the colors to saturate to more clearly show the variations at lower altitudes. At the equator, above 80 km, the ozone and temperature SAO are essentially in phase with each other as a function of day-of-year. With decreasing altitude from 80 to around 35 km, the ozone and temperature SAO are qualitatively out of phase with each other. However, from 80 to about 50 km, the temperature displays a more pronounced phase progression with decreasing altitude. From 50 to about 30 km, the ozone appears to have a larger phase progression as the altitude decreases, so that from about 35 to 25 km, the ozone and temperature are again more in phase, although there may be a lag of about 2 weeks. At 40°N latitude, with decreasing altitude from 80 to around 35 km, the ozone and temperature SAO are essentially out of phase with each other, and each displays a downward progression in phase. Near 35 km the downward phase progression of the temperature ceases, so that near 20 km, the ozone and temperature SAO are mostly again in phase, with perhaps a phase difference of about two weeks. Bevilacqua *et al.* [1990] and Marsh and Smith [2003] indicated that the existence of mesospheric semiannual variations in ozone at mid-latitudes is not consistent with the annual variations shown in water vapor data. Bevilacqua *et al.* [1990] had pointed to the bulge (discussed earlier) between 75 and 80 km in the SME ozone data, which we also see in the SABER data (Figure 4a). Again, we believe that the bulge(s) in Figure 4a are due to diurnal variations

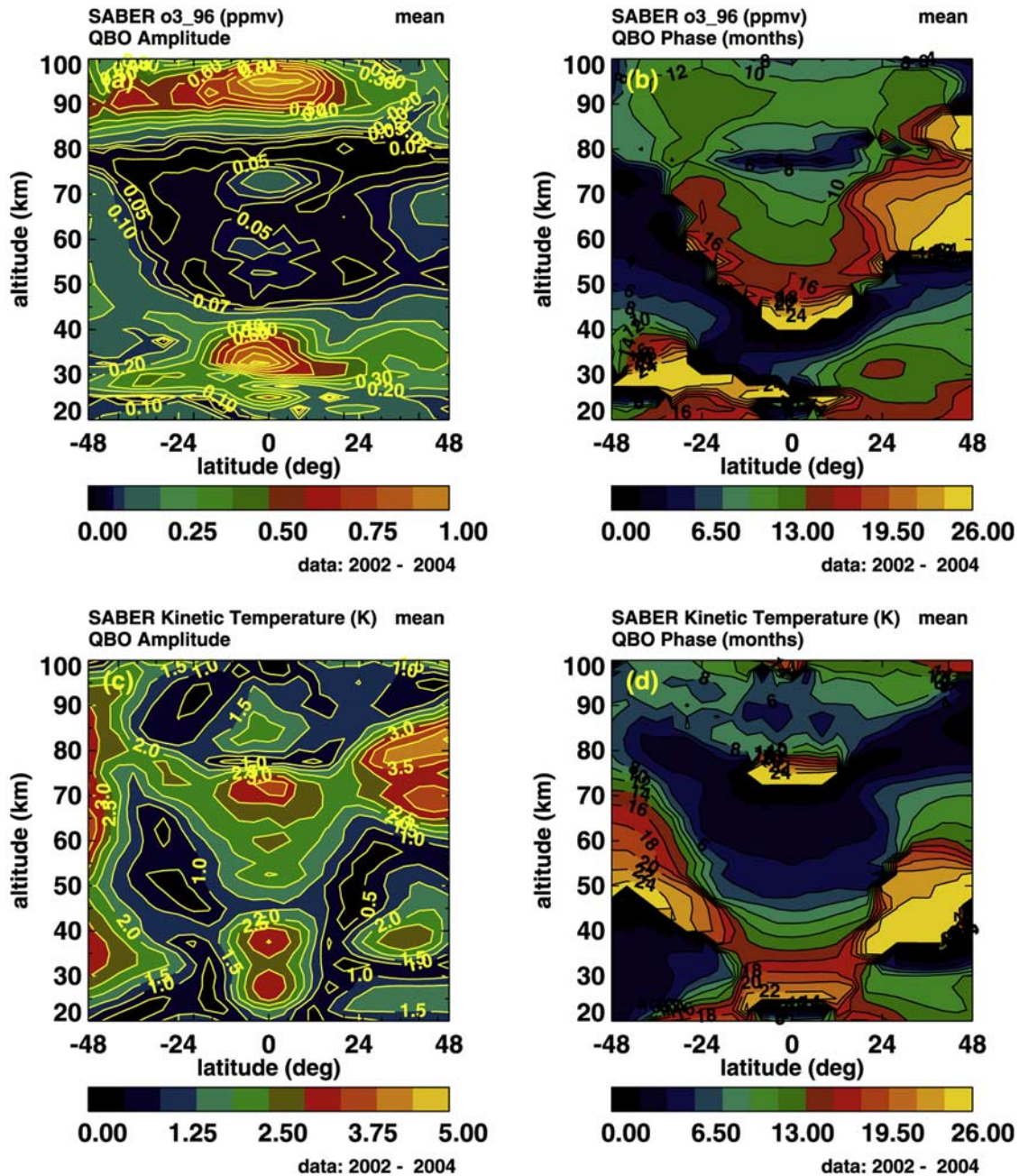


Figure 7. Top row: Derived QBO amplitudes (left) and phases (right) based on SABER ozone mixing ratios (ppmv) on altitude (20 to 100 km) versus latitude (48°S to 48°N) coordinates, based on data from year days 2002001–2004060, assuming 26-month period. Lower row: as in top row, but for temperatures (K). Contour interval for temperature amplitude is 1 K, and 4 months for the both phases. Contour levels are not regular for the ozone amplitude.

with the larger afternoon values. The diurnal variations themselves exhibit semi-annual variations separately from the mean SAO. *Schneider et al.* [2005], using data from the microwave radiometer at Bordeaux, France (44.83°N, 0.52°W) also found semiannual variations in mesospheric ozone, but present representative daytime and nighttime results separately. *Nagahama et al.* [2003] reported on ozone semiannual variations in the mesosphere (60 and 76 km altitude) with data from a millimeter-wave radiometer at Tsukuba, Japan (36.1°N, 140.1°E). They find that

there are significant semiannual variations, with the phase ‘suddenly’ inverting at around 68 km. It is not clear how ‘sudden’ the phase change is, because *Nagahama et al.* [2003] do not provide results in between 60 and 76 km. It can be seen in Figure 8b (top right) and 10c (lower left) that we also see evident phase changes between 60 and 76 km, although the overall shift is somewhat smaller, and is part of a smoother phase progression between 60 and 76 km. That the semiannual amplitudes (about 0.5 ppmv) of *Nagahama et al.* [2003] are significantly larger than ours (less than

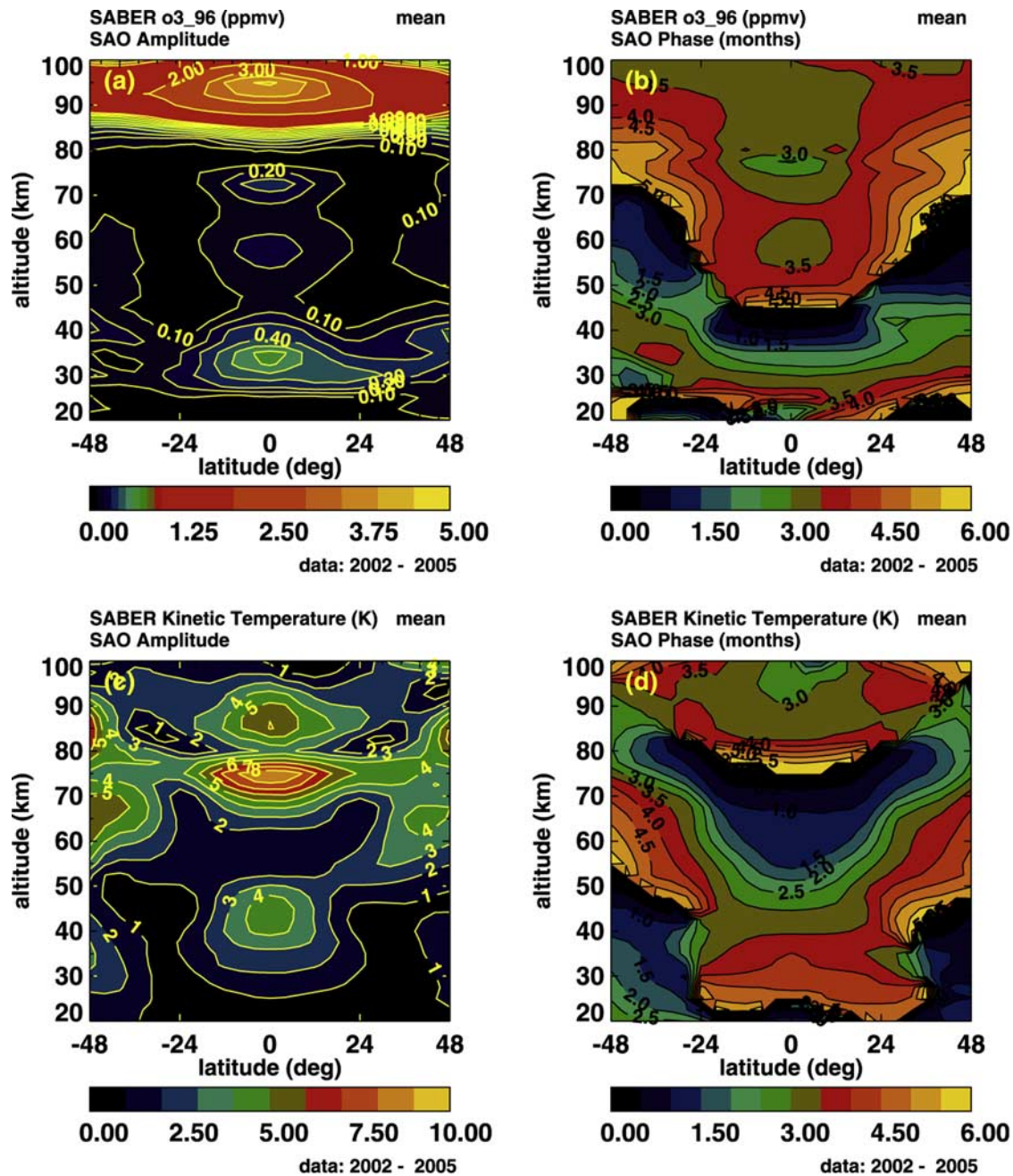


Figure 8. Upper row: derived semiannual amplitudes (left) and phases (month of max value) based on SABER ozone mixing ratios (ppmv, years 2002–2005), on altitude (20 to 100 km) versus latitude (48°S to 48°N). Lower row: as for upper row, but based on SABER temperatures (K). Contour interval for temperature amplitude is 1 K, and 0.5 month for the both phases. Contour levels are not regular for the ozone amplitude.

0.1 ppmv at 75 km and 36°N) can be explained because they purposely used only nighttime data which are ‘enhanced’, in order to increase the signal-to-noise ratios.

5. Summary and Discussion

[37] Ozone and temperature measurements from SABER form a unique data set. They provide global information over 24 h in local solar time, from the lower stratosphere

into the lower thermosphere, over 5 years (2002–2006), by one instrument.

[38] Based on SABER data, we have derived zonal mean ozone mixing ratios of diurnal variations, semiannual oscillations (SAO), and quasi-biennial oscillations (QBO) as a function of altitude (20–100 km), latitude (48°S to 48°N), and day, over an annual cycle and more. Results of the ozone diurnal variations are described in Huang *et al.* [2008]. We have also derived corresponding mean temperature variations. Diurnal variations of ozone become

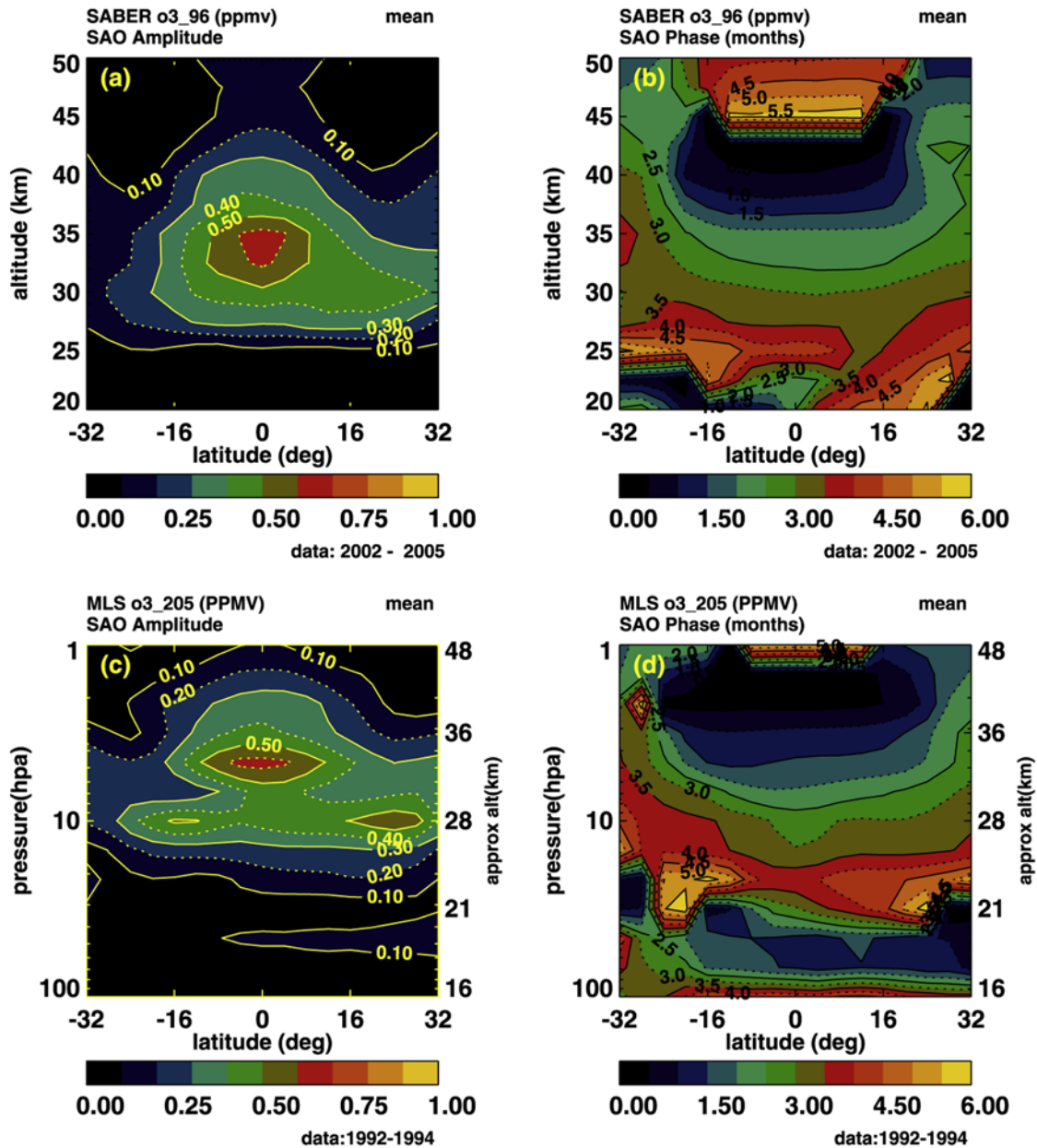


Figure 9. Top row: a subset of top row of Figure 8 to better compare with corresponding results based on MLS data (lower row). Derived semiannual amplitudes (left) and phases (month of max value) based on SABER ozone mixing ratios (ppmv, years 2002–2005), on altitude (20 to 50 km) versus latitude (32°S to 32°N). Bottom row: as in upper row, but based on MLS data (years 1992–1994). The MLS results are plotted from 100 to 1 hPa (~16 to 48 km). Contour interval for the ozone amplitudes is 0.1 ppmv, and 0.5 month for the phases.

increasingly significant from the upper stratosphere into the mesosphere and thermosphere, and our comprehensive results in these regions are essentially all new. The SAO and QBO have been reported and analyzed previously in the stratosphere and below, and we have compared with some of these results, with new details.

[39] In the MLT, it is difficult to reach conclusions from comparisons with previous results due to a lack of comprehensive results, to the relatively large uncertainties of the measurements, and to the large magnitudes of diurnal variations. The enhanced uncertainties are due largely to

the departure from local thermodynamic equilibrium (non-LTE), and the large diurnal variations make it important for different correlative data to be made at the same local time.

[40] Because there are no previous results of the QBO and SAO in the MLT with which to compare, we have taken the approach of making sensitivity estimates and studying correlations with corresponding temperature results, also based on SABER data [Huang *et al.*, 2006c]. In addition, the QBO and SAO are relatively small departures from the mean state, and this mitigates the systematic uncertainties, so the results should be more robust. To support this view,

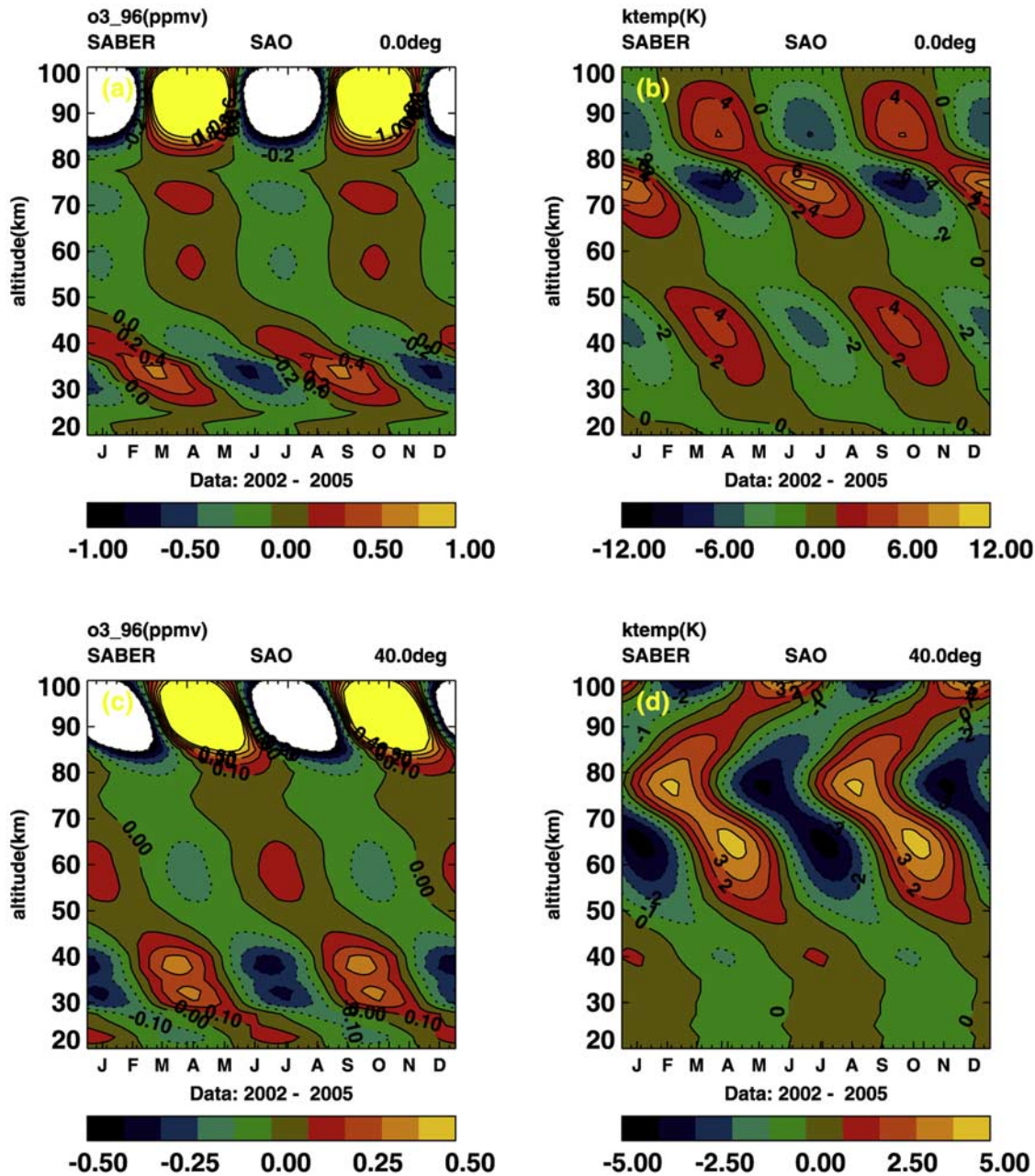


Figure 10. Upper row: semiannual ozone mixing ratios (ppmv, left, (a) and temperature (K, right, (b)) at the equator, on altitude (20 to 100 km) versus day coordinates, based on SABER data (years 2002–2005). Lower row: as in upper row, but at 40°N latitude. Contour intervals are 0.2 (top row left) and 0.1 ppmv for ozone, and 2 K (top row right) and 1K for temperature. Solid contours denote zero and positive values; dashed lines, negative values.

we have analyzed the small ozone bulge between 75–80 km, as discussed in reference to Figure 4 above. The bulge (s) are also seen regularly in the SME data, and have been the subject of other studies in the literature. It is possible that the bulge is due to the local time at which data were taken, and is a reflection of ozone diurnal variations. Our results show that, with the exception of a narrow altitude interval near 80 km, the mean daytime ozone mixing ratios are generally smaller than the nighttime values (Figure 4b). This is also consistent with the ROSE model [Smith, 2004, Figure 4], where the mean daytime values are larger than the

mean nighttime values only near 80 km. If verified, this new explanation of the SME bulge not only is significant for interpretation, it attests to the validity of SABER data and to our analysis. In addition, our results show that the diurnal variations themselves follow a semi-annual variation, which is consistent with the reported semi-annual variation of the bulges in the SME data.

[41] Our analysis of correlations with temperature is interesting from the scientific view and also helps validate the results. In the stratosphere, there are previous results, and the comparisons are very good, including ozone tem-

perature QBO phase relationships. That these phase relations continue smoothly into the mesosphere (cf. Figure 6) supports the validity of the results. The correlations can also indicate the relative importance between chemistry and dynamics. Away from the equator, the phase relationships are mostly systematic as well. We find that ozone and temperature QBOs are more in phase above about 80 km and below 30 km, and more out of phase between about 30 and 80 km, although there are some variations depending on latitude. Our estimates based on data that are two years apart are consistent with the QBO having slowly varying periods, phases and amplitudes, again supporting the validity of the data. Within about 40° of the Equator, the semiannual phases of ozone and temperature are generally symmetric about the Equator, are also mostly out of phase with each other between about 35 and 80 km, and mostly in phase above about 80 km and below about 35 km. Comparisons with previous results (MLS, SBUV) in the stratosphere are very good.

[42] Although not the focus of this paper, we find that the ozone diurnal variations themselves exhibit a semi-annual variation. This has ramifications in the interpretation of the ozone mean SAO. For example, the SME ozone data are all measured near 16 h local time. Depending on the location, semiannual variations of this data could be in part due to those of the diurnal variations. This is also true of some results based on ground-based measurements discussed above that present the semiannual variations for nighttime and daytime separately.

Appendix A: Data Analysis Algorithm

[43] For a given latitude and altitude, the algorithm performs a two-dimensional Fourier least squares analysis in the form

$$\Psi(t_1, d, z, \theta, \lambda) = \sum_n \sum_k b_{nk}(z, \theta, \lambda) e^{i2\pi n t_1} e^{i2\pi k d/N} \quad (A1)$$

where $\Psi(t_1, d, z, \theta, \lambda)$ represents the input data; z is altitude; d is day of year; θ latitude; λ longitude (radians); t_1 = local solar time (fraction of a day) = $t + \lambda/2\pi$; t = time of day (fraction of day), and N is the number of days in the fundamental period. For example, if we analyze data over one year, then $N = 365$.

[44] In this study, we apply the algorithm to data averaged over longitude, although it has been applied to data with longitude variations as well [Huang and Reber, 2004]. For variations with longitude, we use data at discrete longitudes $\{\lambda_i\}$ to find the set $b_{nk}(z, \theta, \lambda_i)$ from (A1). To analyze the behavior with longitude, we estimate $\alpha_{mnk}(z, \theta)$ from

$$b_{nk}(z, \theta, \lambda_i) = \sum_m \alpha_{mnk}(z, \theta) e^{i2\pi m \lambda_i / 2\pi} \quad (A2)$$

again using a least squares fit. Finally, for any day of year d_0 , we can sum (A1) over k to obtain

$$\Psi(t, d_0, z, \theta, \lambda) = \sum_m \sum_n \beta_{nm}(z, \theta) e^{i2\pi m \lambda / 2\pi} e^{i2\pi n t} \quad (A3)$$

where we use β_{nm} to denote the transform to universal time t (fraction of a day).

[45] If we average the data over longitude, then we obtain the migrating diurnal variations and mean flows [Huang and Reber, 2004] from (A1), where the coefficients are no longer dependent on λ . Once we have estimated the coefficients in (A1) or (A3), we can directly generate the diurnal variations for composition, winds, and temperature as a function of day of year, longitude, and time. TIMED sampling patterns are such that data at latitudes poleward of about 50° are made only for alternate yaw periods. Therefore, our current analyses are made only within 48° of the Equator.

[46] Our fits to the data are based on data over a period of one year or more. Currently in (A1), the maximum value of n is 5 for ozone, and the maximum of k depends on the fundamental period in day of year. Because it takes SABER 60 days to sample over the range of local times, when the fundamental day-of-year period is 365 days, we estimate the coefficients $b_{nk}(z, \theta, \lambda_i)$ for k greater than or equal to 3 only for $n = 0$, and the maximum of k is 6. When the fundamental period corresponds to the QBO, the number of terms for day-of-year is scaled up accordingly. The current version of the data do not provide for uncertainties, and we also assume that the uncertainties of the data are proportional to the data values themselves.

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